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Research on The Characteristics of Bearing Behavior of The Profiled Throttling Cavity Air Bearing

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Abstract

The finite volume method was used to study three freedom special throttling cavity characteristics. Based on the internal flow field simulation of three degrees of freedom the profiled throttling cavity air bearing analysis of bearing, analyzed effective of rotating speed and gas pressure on the air bearing characteristics and the different carrying capacity between profiled and conventional structure of air bearing is compared. The results show that, with three degrees of freedom profiled throttling cavity a characteristics have a nonlinear relationship with gas pressure and rotating speed, in order to make the bearing capacity in the optimal value, it should make supply pressure and bearing speed to be limited; special-shaped throttling cavity structure, compared with the conventional throttling cavity structure, at the same condition, the carrying capacity has a larger increase, profiled throttling cavity air bearing has more excellent bearing capacity.

Keywords: Gas lubrication, Throttling cavity, Numerical simulation, Finite volume method.

Nomenclature

ρ_a	Gas density(kg/m^3)
P_r	Environmental pressure(Pa)
μ	Gas viscosity$(\mathrm{N} \times \mathrm{s}/\mathrm{m}^2)$
k	Gas heat capacity

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1. Introduction

Multi degree of freedom air test-bed is currently the world's advanced physical simulation equipment of satellite attitude control system, it can be in a more realistic simulation of satellite in space dynamics, exchange of momentum, momentum coupling on the ground, thereby timely discover the practical model the possible problems. The air bearing already had history of nearly 50 years using in spacecraft attitude control and the corresponding hardware and software development. As the key components of air test-bed, gas bearing has a wide application prospect with almost zero friction, no wear, no pollution, high rotation accuracy, can be used in high temperature and low temperature stability and other characteristics, when compared with other supporting forms, in the space of three axis simulation device and other fields. Three degree of freedom air test-bed working by the film which is formed by compressed air between the floating bearing and the bearing seat makes the satellite simulating platform floating, thereby achieving nearly frictionless motion. The typical of the three degrees of freedom air test-bed has the following three kinds of configuration, as shown in

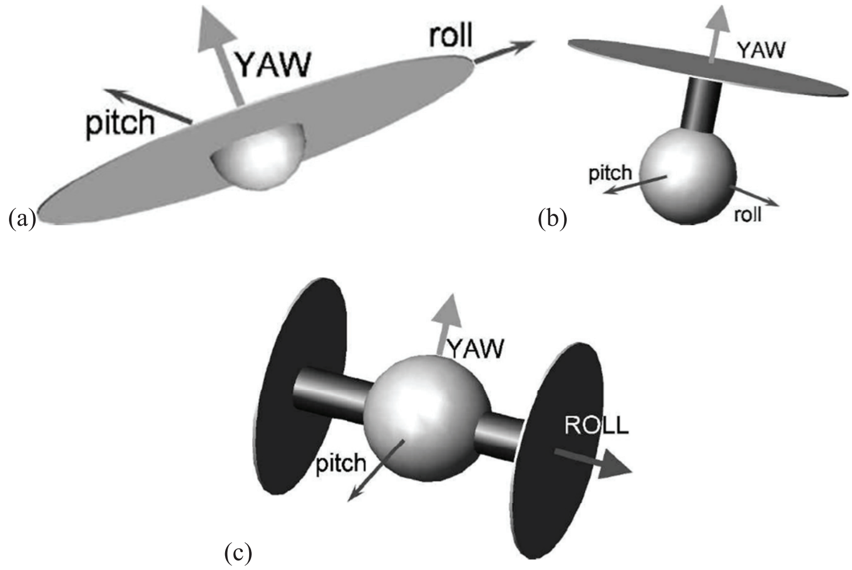


Fig. 1 Typical three DOF air bearing test bench configurations (a) table model (b) umbrella model (c) dumbbell model.

Among them, in the flat configuration and umbrella configuration, the load is fixed on the platform, it has 360 degrees of rotational freedom through a spherical hinge rotate around the yaw axis, however, due to structural constraints, the pitch angle and roll angle are limited in 90 degrees; the third types of flotation test-bed, due to the symmetry in structure, obviously reduces the load bearing platform and the motion interference, it can provides a three axis free movement.

The traditional dynamic and static pressure air bearing, research aspect of structure design, mainly concentrated in the dynamic pressure groove types and parameters selection [1]. Usually the step surface, a rotary chute, a miter slot structure were adopted [2-4]. The grooves above have a common feature, namely with the groove depth is fixed. When theoretical analyzing these structures, the design methods are more comprehensive and mature. With the air bearing applications more widely, it has a higher requirements of the dynamic and static pressure bearing performance. At present, the researches on bearing performance are focused on traditional bearing structure parameter optimization design. However, for variable depth of cavity shaped throttling cavity structure bearing, because of the significantly nonlinear characteristics, its design theories are not perfect. Thus, carrying characteristics need to be studied.

In this paper, the throttling cavity structure of three degree of freedom spherical static pressure bearing has been researched using the numerical simulation based on the finite volume method [5]. First of all, through the establishment of the corresponding mathematical model, by changing the rotating speed and air supply condition, researching the characteristic of bearing capacity; then, compared with the conventional structure of dynamic and static pressure spherical air bearing, the characteristics of deep cavity shaped throttling cavity structure has been researched.

2. Modeling and simulation

When analysis air bearing characteristic, the traditional methods are usually applied to finite element method; this method mainly by conformal transformation, the three-dimensional calculation is simplified into two dimensions [6]. This method is in a two-dimensional Reynolds equation, but in the real process, there will be bearing partial load or entrance boundary asymmetric, and two-dimensional Reynolds equation cannot accurately simulation the operation. Thus using the finite element method, there is a relatively large amount of calculation, if the grid is too much, it will cause the solving speed sudden drop. Therefore, using the finite element method to calculate, many cause drawbacks in application. While the commercial finite element software application, through the early establishment of three-dimensional model to simulate the actual flow. Through the pretreatment process for grid node distribution control and the boundary conditions settings, it can simulate the actual working conditions of air bearing in the supply pressure and other parameters, and the bearing system would be simulated [7].

Through the establishment of 3D model, using finite volume method to analysis, in the process of gridding, using a large aspect ratio structured grid, and then set the effective boundary conditions, flow field has been simulated, and got the bearing pressure distribution and velocity distribution.

2.1. Basic model

Profiled the throttling cavity structure has bigger distinction compared with the standard of gas cavity structure. First of all, a variable cavity was designed, in a high speed rotating situation, the cavity flow in bearing, produced a wedge effect because the gas film thickness becomes smaller gradually, and dynamic pressure effect was significantly enhanced. In the same time, along the direction of operation of the bearing, gas cavity adopts a variable diameter design form, also increased the dynamic pressure effect in the operating process.

Supposed hemispherical bearing ball diameter is 2R=25mm, the maximum load is 111KN. Through calculation, can get the bearing structure dimensions, parameters can be seen in Table. 1.

Table 1. Structural parameters of 3-D hybrid air bearing.

Geometric parameters	value
Spherical radius（r/mm）	12.5
External wrap angle（φ1/°）	30
Supply holes wrap angle（ϕs/°）	60
Internal wrap angle（φ2/°）	90
Supply holds numbers	6
Rolling hole diameter（mm）	0.33

Throttle cavity numbers	6
Supply hole diameter	4
The throttling cavity in large diameter D1（mm）	2
The throttling cavity in small diameter D2（mm）	1
Center distance L (mm)	3.3
Slot width H(mm)	1
Stomata axis angle	15°

The bearing gas cavity structure model as shown in Fig. 2:

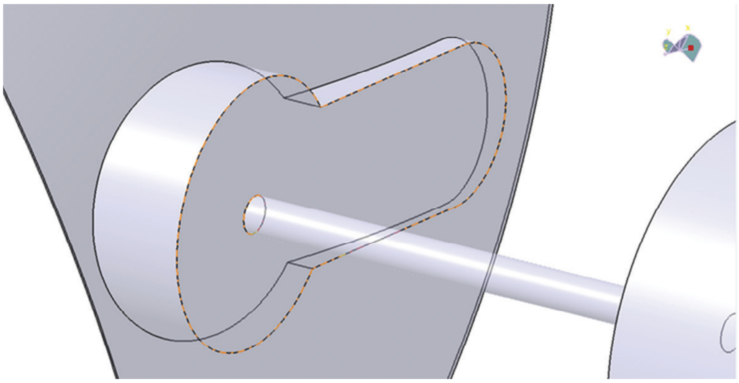


Fig. 2 3-D dynamic and static pressure spherical bearing gas cavity structure diagram.

2.2. Meshing generation

Because the film gap thickness is very thin, and is a minimum value when compared with the bearing size, usually processing method for film thickness is to ignore, be simplified as a two-dimensional plane, it can bring certain convenience the application of finite difference method to solve the N-S equation. However, due to the model to make too many assumptions, the calculated results are contrast with actual situation, and it may cause significant deviation. Using CAD model to simulate the film structure, it can be avoided that deviation because of the excessive simplification model, which causing phenomenon of gas film flow field inside information loss. In this paper, using hexahedral grid to build the film clearance structure grid, the grid generation focuses on film clearance and air supply position. In theory, the model grid number is more, the higher the calculation precision, but the computation time will be longer, after comprehensive consideration of grid number, determined the number is 2,570,000.

The Gas film and throttle area are the key parts for calculation, and should be refinement. In addition, in order to ensure the quality and quantity of grid, it should not to make the film height direction`s grid too dense, in this paper, using hexahedral mesh partially encrypted grid as shown in Fig. 3.

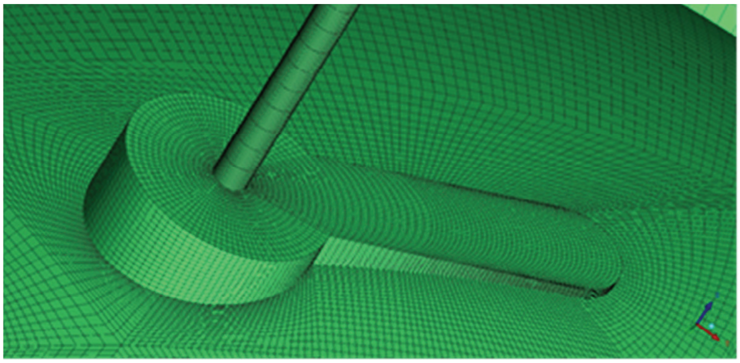


Fig. 3. 3-D spherical hybrid bearing flow field calculation grid.

2.3. The simplified boundary conditions

Considering the actual internal gas flow is a complex three-dimensional flow process, in order to reduce hardware requirements for the simulation, simplified the calculation, making the following assumptions:

- Both bearing and the rotor face are ideal smooth surface, average and the thickness as a constant value.
- Gas flow process in the gas film is short, the heat does not exchange, so that gas flow is insulation.
- In the research of the three degrees of freedom dynamic and static pressure spherical air bearing static characteristics, the main concern is the macroscopic characteristics of gas film, in order to save the simulation time, using the steady model to calculate [8].

As above assumptions, the gas constant and the air pressure`s setting were shown as Table. 2, the gas outlet pressure was set as ambient pressure.

Table. 2 Lubricate gas parameters.

parameters	value
ρ_a	1.204
μ	1.82×10^{-5}
k	1.401
P_r	101325

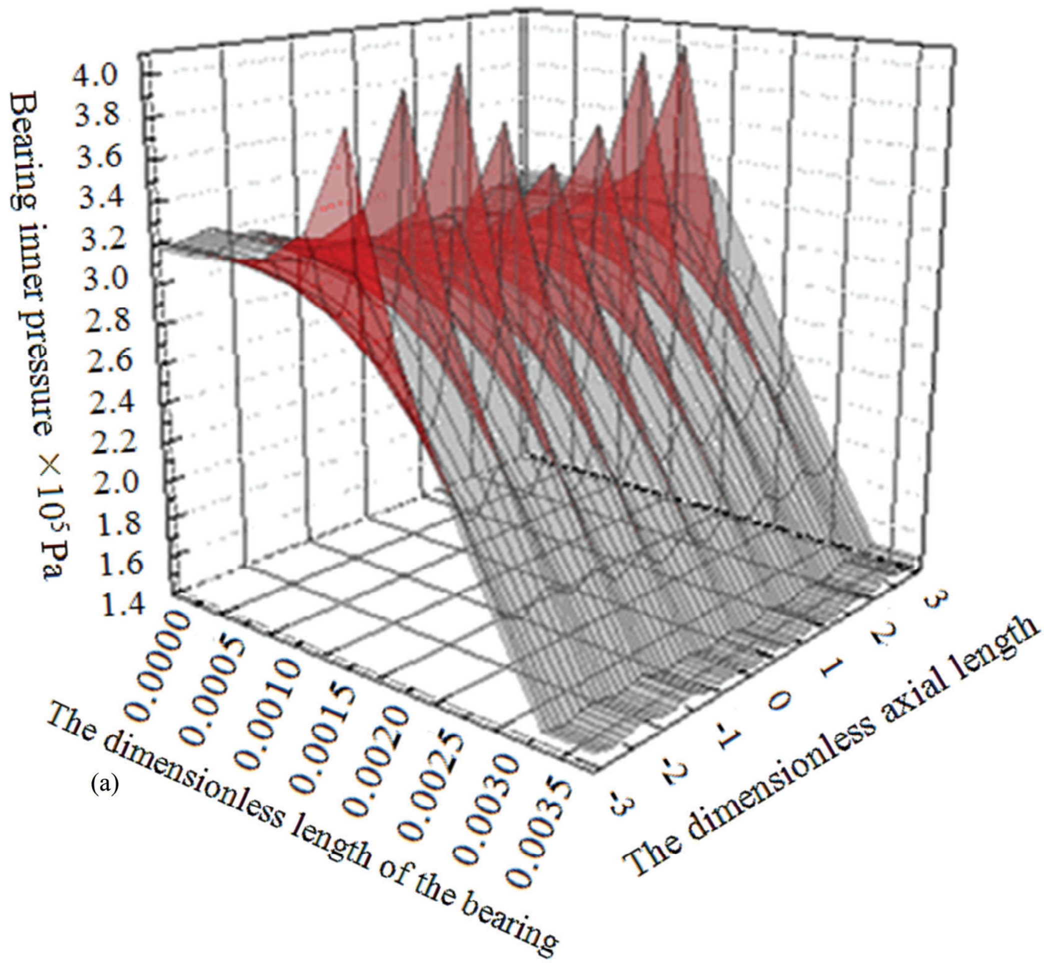
3. The static charateristic simulation based on finite volume method

3.1. Simulation verification

In order to verify the numerical simulation based on finite volume method, first of all using the air bearing shown in [9] as an example. Analyzed the gas film pressure distribution simulated based on the fluent, and contrast with the previous theoretical analysis results.

Fig. 4shows the gas film pressure distribution under the eccentricity e=0.2, bearing speed for 100000r/min, as shown in the graph, the pressure distribution obtained on the finite volume method is same as the theoretical analyzed results, in which the pressure along the circumferential direction changes due to the different attitude angle. From the contrast shown in the picture, more detailed of the internal gas pressure changes can be shown by using finite volume method. For the different between Fig. 4 a) and fig b), on one hand, the theoretical research model assumptions and the actual situation are not consistent; on the other hand, through the assumption conditions analyzed in [9], it introduced the film throttle in process of analyzing, caused the pressure distribution changes, gas pressure in the high pressure region is higher pressures and in area of low pressure is much lower.

However, based on the results of the two methods, in a throttle area, gas film pressure distributions are basically same. Therefore, in general, the finite volume method can be taken as analysis method in the dynamic and static pressure air bearing coupling.



(a)

(b)

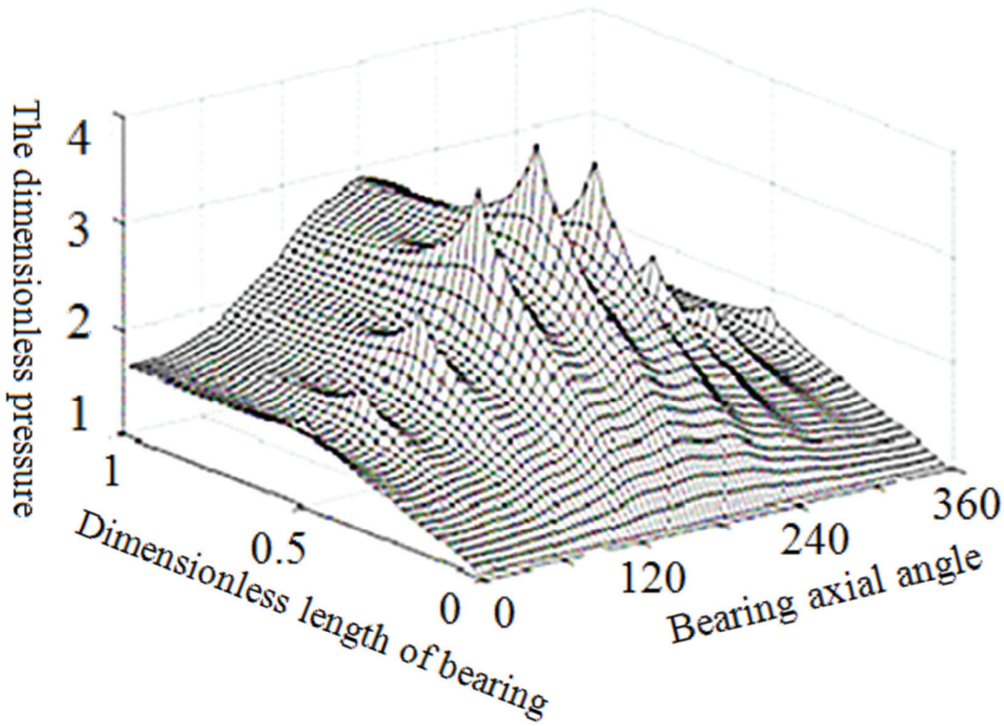


Fig. 4 the simulation results (a) in comparison with the theoretical results (b).

Static pressure and dynamic pressure effect are mainly affected by the gas pressure and the rotating speed in the operation process of static and dynamic air bearing when the structure parameters are fixed. In order to analysis the bearing characteristic of three degrees of freedom dynamic and static pressure spherical air bearing under static affect and dynamic affect, studied separately.

3.2. Bearing ability under the condition of different pressure

The bearing characteristics have relationship with gas pressure when the structure parameters and bearing speed are fixed, in order to study the inherent laws, setting several kinds of initial and boundary conditions, and the corresponding bearing capacity are compared.

Due to dynamic effect and static effect coupling in dynamic and static air bearing, in order to reduce these couple effect, the bearing speed is set as a low value. In this example, the bearing wall surface speed is set to 100rad/s, support pressure was set as 1Mpa, 1.5Mpa, 2.03Mpa, 2.5Mpa, 3Mpa respectively, outlet pressure was ambient pressure, the curve bearing capacity changing with the gas pressure as shown in Fig. 5.

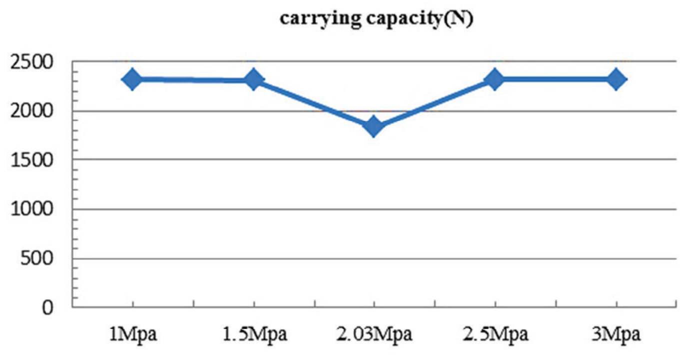


Fig. 5 Bearings carrying capacity change under different supply pressure.

Through Fig. 5, the air bearing capacity changing and the air pressure has nonlinear relationship, when the pressure is 2.03Mpa, the air bearing carrying value was the lowest.

3.3. Bearing ability under the condition of different rotate speed

In order to study the dynamic pressure effect on the static and dynamic air bearing capacity under with different speed conditions, set gas pressure value was 2.03Mpa, outlet pressure set as ambient pressure, and rotate speed was 100rad/s, 500rad/s, 1000rad, /s, 5000rad/s, 10000rad/s respectively. The curve bearing capacity changing with the rotating speed was shown in figure 6.

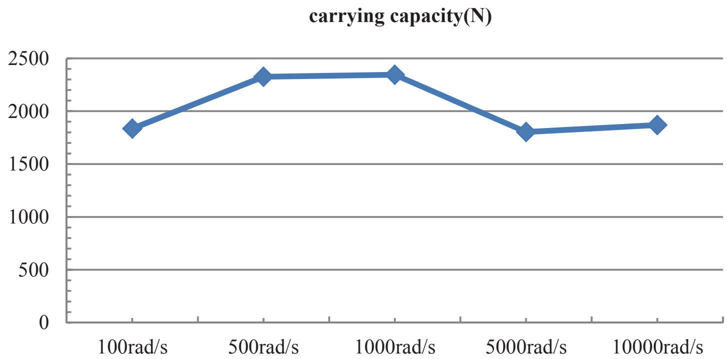


Fig. 6 Bearings carrying capacity change under different supply pressure.

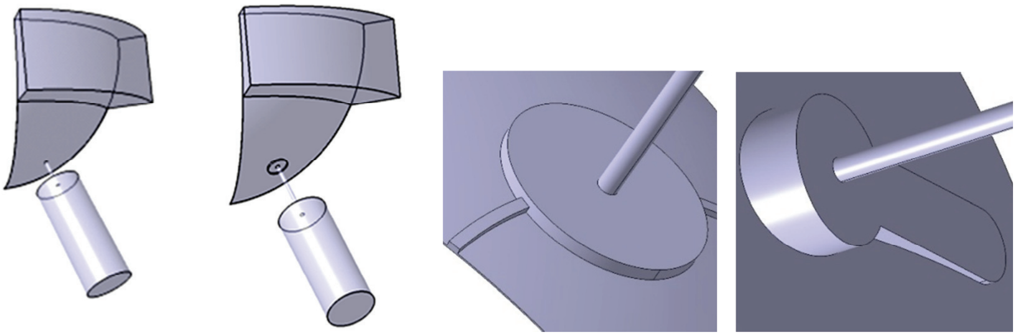
Through Fig. , when the air pressure at a certain value, bearing capability has nonlinear relationship with rotating speed. The bearing capability is lower when the rotating speed was in the lower (100rad/s) or higher (5000rad/s), compared with moderate speed (500rad/s-1000rad/s).

3.4. Bearing ability under the condition of different structure

In order to study the different between variable cavity depth and shape throttle cavity spherical air bearing and using a constant depth of throttle cavity spherical air bearing, using the same initial conditions and boundary conditions, simulated different throttle structure bearing with the same spherical radius respectively. In contrast with the constant throttle cavity depth under spherical coordinate system, its structure as shown in Fig. 7. Among them, a) for 1/6 no throttle cavity structure, b) 1/6 5 times diameter shallow throttle cavity structure, c) 1/6 10 times diameter shallow throttle cavity structure, d) 1/6 10 times diameter shallow throttle cavity structure with pressure-equalizing groove. These structure parameters such as shown in Table. 3.

Table. 3 Different throttle structure parameters.

Geometric parameters	a)	b)	c)	d)
Spherical radius（r/mm）	12.5	12.5	12.5	12.5
External wrap angle（φ1/°）	30	30	30	30
Supply holes wrap angle（ϕ_2/°）	60	60	60	60
Internal wrap angle（φ2/°）	90	90	90	90
Supply holds numbers	6	6	6	6
Rolling hole diameter（mm）	0.33	0.33	0.33	0.33
Throttle cavity numbers	6	6	6	6
Inlet pressure diameter（mm）	4	4	4	4
Throttle cavity diameter（mm）	0	1.65	3.3	3.3
Stomata axis angle	0°	0°	0°	0°
Pressure-equalizing groove wrap angle（φ3/°）	/	/	/	60°
Pressure-equalizing groove width (mm)	/	/	/	0.2
Pressure-equalizing groove depth (mm)	/	/	/	0.1



(a) (b) (c) (d)

Fig. 7 Different throttle structure diagram.

Researching different throttling cavity structure`s effect on the static and dynamic air bearing properties, mainly focused on air bearing dynamic pressure effect. In this article, the boundary conditions and initial conditions were set as follows: support pressure was 2.03Mpa, outlet pressure set as ambient pressure. Studies the five different throttle structure bearing characteristics under the rotation speed was 100rad/s, 1000rad/s, 10000rad/s respectively.

When the rotating speed was 100rad/s, different throttle structure bearing characteristics as shown in Table. 4:

Table. 4 100 rad/s Different throttle structure bearing capacity and rotational resistance.

Throttle structure form	Bearing capacity (N)	Rotational torque (N·m)

No throttle cavity structure	76.80	7.644E-06
Standard throttle cavity structure	54.03	9.464E-06
Small throttle cavity structure	93.96	1.473E-05
Throttle cavity structure with pressure-equalizing groove	30.40	8.346E-06
Profiled throttle cavity structure	1835.00	1.500E-02

When the rotating speed was 1,000rad/s, different throttle structure bearing characteristics as shown in Table. 5:

Table. 5 1,000 rad/s Different throttle structure bearing capacity and rotational resistance.

Throttle structure form	Bearing capacity (N)	Rotational torque (N·m)
No throttle cavity structure	77.67	9.315E-05
Standard throttle cavity structure	56.28	9.061E-05
Small throttle cavity structure	103.80	1.114E-04
Throttle cavity structure with pressure-equalizing groove	31.35	8.714E-05
Profiled throttle cavity structure	2344.00	1.862E-02

When the rotating speed was 10,000rad/s, different throttle structure bearing characteristics as shown in Table. 6:

Table. 6 10,000 rad/s Different throttle structure bearing capacity and rotational resistance.

Throttle structure form	Bearing capacity (N)	Rotational torque (N·m)
No throttle cavity structure	82.13	1.013E-03
Standard throttle cavity structure	66.03	1.144E-03
Small throttle cavity structure	68.31	1.103E-03
Throttle cavity structure with pressure-equalizing groove	30.96	1.590E-03
Profiled throttle cavity structure	1869.00	1.506E-02

By contrast it can be found that air bearing which using profiled throttling cavity has obvious advantages compared with the ordinary throttling cavity structure air bearing in bearing capacity. In the 100rad/s speed, using profiled throttle structure air bearing capacity increased by 1852.96%, in the 1,000rad/s speed, using profiled throttle structure air bearing capacity increased by 2158.19%, in the 10,000rad/s speed, using profiled throttle structure air bearing capacity increased by 2175.66%. The results shows that in three degrees of freedom of dynamic and static spherical air bearing, the variable cavity depth, and the variable cross-section throttling cavity structure, can improved the bearing capacity obviously.

4. Conclusions

Through the above analysis, the following conclusions can be drawn:

- Three degrees of freedom dynamic and static pressure spherical bearing load capacity and nonlinear relationship with supply pressure, in order to get the air bearing great bearing capacity, it should be reasonably controlled gas pressure range.
- Due to dynamic pressure effect, in different speed conditions, air bearing load characteristics shows obviously nonlinear characteristics. Therefore, in the study of dynamic and static pressure coupling effects should be considered both dynamic and static pressure effect, rather than separate analysis.

- Using profiled throttle structure air bear bearing has obvious advantages than ordinary throttle structure in bearing capacity, it can significantly improve the axial bearing capacity.

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